11. STUDIES OF ATMOSPHERIC ATTENUATION OF NOISE

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INTRODUCTION

Everyone who works with outdoor sound measurements quickly becomes aware that the atmosphere is a very unsatisfactory propagation medium. It greatly attenuates sound at high frequencies, with coefficients varying widely from hour to hour and day to day. The atmosphere is almost always in motion and is characterized by turbulence, stratified layers, gradients, and inhomogeneities especially near the ground surface. The velocity of sound in air is temperature sensitive and slow enough that Doppler shifts due to winds, engine-generated airflow, and vehicle motion cannot be neglected.

To study atmospheric effects on sound propagation, it is necessary to start with simplifications and gradually approach a more realistic model. It should not be surprising that the classical assumption of a homogeneous, stationary atmosphere does not give an entirely satisfactory result. Yet it is on such an assumption that reference 1, the Society of Automotive Engineers standard on atmospheric absorption corrections, Aerospace Recommended Practice 866 (ARP 866), is largely based.

It has become popular to criticize ARP 866. The large corrections it calls for at high frequencies seem to be unreasonable, and when they are applied to much of the fly-over data, they lead to absurdities, such as a noise level which increases as the airplane gets more remote. Such results have led to restrictions on the range of temperature and humidity within which experimental data are acceptable. These restrictions in turn cause extra complications in flight-test scheduling and frequently cause delay and added expense. As a result, The Boeing Company, in conjunction with NASA, has undertaken to find answers to questions like the following:

(1) Is ARP 866 based on sufficiently well-established theoretical grounds?

(2) Does ARP 866 fit reasonably well with experimental results?

(3) Are there other measurement factors which can account for the unsatisfactory results which are often obtained?

(4) Can the accuracy of data be improved and the range over which measurements taken be increased, either by modifying ARP 866 or by changing instrumentation and/or data processing?

DISCUSSION

ARP 866 is based on the work of recognized authorities in the field, particularly Kneser and Harris. (See refs. 2 and 3, respectively.) In the words of the ARP document (ref. 1), "The experimental results of Harris were obtained for a single temperature of 20° C (68° F). Essentially, these data were used, and curves based on Kneser's theory were 'modified' to fit them." More recently, Harris has extended his laboratory experiments to include a range of temperature, but these results have not been incorporated into ARP 866.

Atmospheric absorption is caused by several mechanisms which convert sound into heat. Within the audible frequency range, however, by far the largest portion of the absorption is caused by the resonant vibration of the oxygen molecules, which is in turn strongly influenced by the presence of water molecules. As a result atmospheric absorption is strongly dependent on humidity. The maximum attenuation which can occur at any frequency, as calculated from Kneser's work (ref. 2), agrees very well with experimental data from various observers. Measurements of the humidity values at which maximum attenuation is obtained and of the attenuation curve for other humidity values have also been made by a great many observers. They show a very wide spread and none agree particularly well with Kneser's theory.

No one has yet been able to explain this discrepancy. The procedure in developing ARP 866 was simply to shift Kneser's theoretical curve to make a reasonable fit with experimental results, most of which were obtained by Harris, whose work is the most extensive and most recent of the laboratory studies. (See ref. 3.) As Harris points out, the measurements are very sensitive to small errors and to boundary losses in the measurement chamber. He has attempted to control these carefully, but the issue will scarcely be settled until either a new measuring procedure results in better agreement with theory or modifications are developed to the theory to bring it in line with present data. The differences are considerable at humidities above those which give maximum absorption, with values according to ARP 866 running to four times the theoretical values in extreme cases. Therefore, the answer to the first question, "Is ARP 866 based on sufficiently well-established theoretical grounds?," must be a rather qualified "yes."

Data from outdoor acoustic measurements almost without exception lead to attenuation values far greater than those from the Kneser theory and, in some instances, larger than values from ARP 866. Data from The Boeing Co., Douglas Aircraft Co., and Rolls-Royce, Ltd., obtained prior to 1962, were considered in the development of ARP 866 and were shown to be reasonably consistent with it. Comparison of more recent data by these three companies plus data from British Aircraft Corp., Ltd., General Electric, and the British National Physical Laboratory shows a rather wide scatter around the ARP 866 values.

Actually, it should not be expected that outdoor measurements, which include atmospheric attenuation and turbulent scatter, will correspond to ARP 866 predictions, which are in theory based on atmospheric absorption only. Most outdoor data include a variety of interference effects and ground absorption phenomena as well as shadowing from thermal and wind gradients. No complete analysis has yet been developed to compensate for all these factors, and it is hard to imagine an adequate array of meteorological sensors to provide a systematic description of the entire path over which the sound from an airplane is propagated. At best, statistically significant data are all that can be hoped for, and inclusion of a wide range of atmospheric conditions is necessary.

TEST PROGRAM DESCRIPTION

Since large amounts of noise data are being collected in Boeing flight tests at the acoustic range at Grant County Airport, Moses Lake, Washington, a procedure has been devised for comparing data from various microphones at different distances, but at a uniform angle with respect to the engine center line. The computer program, after adjusting for spherical divergence, automatically plots differences in sound level between pairs of microphones and draws the best fit straight line through the values. The slope of the line gives the attenuation coefficient.

The data used in the present analysis were obtained during a flight test program conducted during February through May, 1969, at Moses Lake and over Puget Sound near Seattle. The purpose of the program was to compare the acoustic and operational performance of a 707-320B airplane equipped with acoustically treated nacelles with that of the same aircraft with production nacelles installed.

The flight program consisted of several series of tests including take-offs, landings, and level fly-bys for both the treated and existing nacelle configurations. (See table I.) Acoustic data were recorded from an array of microphones along the center line and to the side of the runway. (See fig. 1.) Tracking radar provided time-correlated aircraft-space-position data during the acoustic test series. From this information, accurate space position of the aircraft was obtained.

Surface temperature, relative humidity, and wind were measured at a central location near the midpoint of the main runway. In addition, conditions were monitored at points near the approach and take-off ends of the runway. Table II shows the range of weather conditions sampled during the various test series, including the level fly-bys over Moses Lake and Puget Sound and the subjective tests at Moses Lake on May 24 and 25, 1969. Some of the flights provide information on the effects of winds above 10 knots and relative humidity below 30 percent, the usual cut-off conditions for accurate testing.

In addition, soundings of temperature, humidity, and wind were made to a height of 3000 feet at intervals during some of the series of flights. Testing was scheduled to take advantage of the higher relative humidity prevailing in the early morning; however, analysis of the radiosonde data shows that the surface measurements may not be representative of the entire atmospheric layer between the aircraft and microphone. A comparison can be made of attenuation coefficients obtained from surface weather measurements with those obtained by using the radiosonde data.

ANALYSIS

The basic problem of aircraft-noise evaluation is obtaining valid measurements. Of equal importance is the availability of accurate normalizing procedures for comparing measurements taken at other distances and conditions.

The present study is concerned with atmospheric attenuation but first considers some of the sources of error and their effects on measurement, analysis, and normalization of noise data.

Figure 2 shows the more important sources of error and distortion in fly-over-noise measurements. The typical jet-engine spectrum as measured in free field between about 45 and 11 000 hertz can be expected to have a rather uniform, smoothly rounded shape reaching a maximum in the vicinity of 1 kilohertz and perhaps falling off by 20 decibels or so at the extremes. Many engines have discrete line spectra or narrow-band noise peaks related to fan, compressor, or other rotating components.

Propagation through the atmosphere selectively attenuates the high frequencies, with absorption values according to ARP 866 of more than 35 decibels per 1000 feet at 8 or 10 kilohertz on a moderately dry day. Since the propagation path may be 5000 feet or more, a spectrum at the ground where the 8-kilohertz level may be as much as 170 decibels below that at 1 kilohertz can be anticipated.

Microphones near the surface also pick up ambient noise from other sources, such as traffic, insects, birds, and so on; this noise sets a noise-floor limit below which the signal cannot normally be detected. On a broad-band basis, this floor is not likely to be lower than 40 to 50 decibels in most outdoor locations. On a 1/3-octave-band basis, centered at 8 or 10 kilohertz, the value could be expected to be perhaps 10 to 15 decibels lower. In practice, it is doubtful if aircraft noise measurements have usually reached this acoustic noise floor because of electrical noise pickup in the input circuits and dynamic range limitations in recording and analyzer components. Thus, it is evident that even with care, it is probably impossible to maintain a dynamic range at the microphone input much in excess of 70 decibels. As shall be seen later, this is usually reduced by other parts of the measurement system.

Another distortion of the input signal is caused by the frequency-selective multipath interference between direct and ground-reflected signals. This interference pattern is considerably modified by the complex impedance and propagation constants of the surface in the case of a porous medium like sod, sand, or gravel. It affects primarily the lower frequency ($\leq\approx$1 kilohertz) components in the case of overflight measurements.

All electronic components introduce some electrical noise, and since they also have an overload distortion level, they have a restricted dynamic range. The magnetic-tape recorder, for example, usually has a potential range of about 48 decibels for broad-band signals. For 1/3-octave-band analysis in the higher frequencies, this range can be increased to about 60 decibels. The analyzer currently in use has a dynamic range of only 40 decibels, but this can be improved by repeating the analysis with a different gain setting or by using other equipment.

In summary, instrumentation usually limits the dynamic range and even with careful attention to equipment use, the dynamic range is at best about 70 decibels. The difference between this dynamic range and the 170-decibel range from atmospheric attenuation explains the unreasonable results that are often observed. Even if the values in ARP 866 are an exact representation of the atmospheric attenuation, application of them to data below or near the noise floor is meaningless. In spite of these restrictions on the accuracy of available data, it is worthwhile to pursue the present analysis with a view to quantifying more precisely the magnitude of uncertainty.

Figure 3 is an example of the type of results produced by the present work to describe attenuation coefficients for various frequencies. The slope of the line of best fit gives the attenuation coefficient for that frequency. In this example the attenuation is 17 decibels per 1000 feet. An attenuation value of 14 decibels per 1000 feet is derived from ARP 866 for the ambient surface temperature (T) and relative humidity (RH) and is shown by the dashed line. Adjustment of the ambient conditions to account for differences between surface and radiosonde measurements results in an ARP 866 derived attenuation of approximately 17 decibels per 1000 feet.

From attenuation values obtained for each 1/3-octave band, a curve of attenuation versus frequency can be plotted for each flight. Figure 4 shows the data for all frequencies above 1000 hertz for the same flight (example 1) as illustrated in figure 3. The attenuation curve from ARP 866 for ambient surface conditions is shown by the dashed line. When adjusted to average temperature and humidity for the entire propagation path, the curve nearly coincides with the measured values between 1000 and 5000 hertz. Above that frequency the effect of the noise floor is distinctively evident.

A similar plot of attenuation using Boeing data from another flight (example 2) is shown in figure 5. The effect of the equipment noise floor begins to be evident at

frequencies above 6300 hertz. The difference between the measured and predicted attenuation at lower frequencies is unexplained at this time.

Data for all temperatures and humidities can be compared with the ARP 866 (Harris) curve for normalized attenuation (α/α_{max}) versus normalized absolute humidity (h/h_{max}). Figure 6 shows the preliminary results obtained from the two flights discussed previously.

CONCLUDING REMARKS

While results presented herein are preliminary, answers to the questions originally posed can be suggested.

The answer to the first question, "Is ARP 866 based on sufficiently well-established theoretical grounds?," is a qualified "yes."

The second question was "Does ARP 866 fit reasonably well with experimental results?" Although this analysis is far from complete at the present time, the indications are that the absorption coefficients which have been determined agree well with ARP 866 values. In fact, it has become evident that a majority of unsatisfactory experimental data cannot be blamed on errors in ARP 866. However, the third question must be answered before a firm conclusion can be reached on the second question, especially at the higher frequencies and for weather conditions much different from the acoustical standard day ($T = 59^{O}$ F, RH = 70 percent). Identification of major limitations in the dynamic range provided by current procedures for using conventional equipment have been made. This obstacle must be overcome if ARP 866 is to be validated or revised. There is no technical reason why this cannot be done, but it will not be done without a very substantial and expensive effort.

Studies are now underway to determine a reasonable way to implement atmospheric corrections without exaggerating noise-floor effects. A technique has been developed to determine the absorption from data which are above the noise floor. It is hoped that the data determined by this technique can be extrapolated to replace values which are below the noise floor. Only portions of the data which are obviously unreasonable would need to be discarded, and absorption values would be based on measurements over the real path through which the sound travels. This path must be determined and measurement of its meteorological properties must be made possible. The only assumptions are that (1) the atmospheric path during the overflight remains reasonably constant, and (2) the acoustic output of the aircraft is statistically uniform during the overflight. Some difficulties are appearing in the extrapolation procedure, particularly for large aircraft where reflections from the wings may substantially modify the directional pattern of the engine.

This complicates not only the noise-floor extrapolation but also the atmospheric attenuation computation and the computation of overflight noise characteristics from static test data. It is believed that this problem can be solved, and, consequently, it should be possible to get acceptable noise measurements over a much broader range.

REFERENCES

1. Anon.: Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity for Use in Evaluating Aircraft Flyover Noise. ARP 866, Soc. Automot. Eng., Aug. 31, 1964.

2. Kneser, Hans O.: The Interpretation of the Anamolous Sound-Absorption in Air and Oxygen in Terms of Molecular Collisions. J. Acoust. Soc. Amer., vol. V, no. 2, Oct. 1933, pp. 122-126.

3. Harris, Cyril M.: Absorption of Sound in Air in the Audio-Frequency Range. J. Acoust. Soc. Amer., vol. 35, no. 1, Jan. 1963, pp. 11-17.

TABLE I.- AIRCRAFT OPERATIONS SUMMARY

Flight condition	Objective tests for –		Subject tests for existing and treated nacelles	Total
	Existing nacelle	Treated nacelle		
Take-off	12	27	---	39
Landing	6	10	7	23
Level fly-by at				
Moses Lake	12	24	36	72
Puget Sound	12	12	---	24
Total	42	73	43	158

TABLE II.- RANGE OF ACTUAL WEATHER CONDITIONS

Weather conditions	Objective tests for –				Subjective tests for existing and treated nacelles at Moses Lake
	Existing nacelle at –		Treated nacelle at –		
	Moses Lake	Puget Sound	Moses Lake	Puget Sound	
Wind speed, knots	2 to 9	--	1 to 9	7 to 8	1 to 18
Temperature, ^{o}F	46 to 59	48	48 to 67	59 to 61	64 to 85
Relative humidity, percent	33 to 60	76	27 to 89	75 to 85	28 to 44

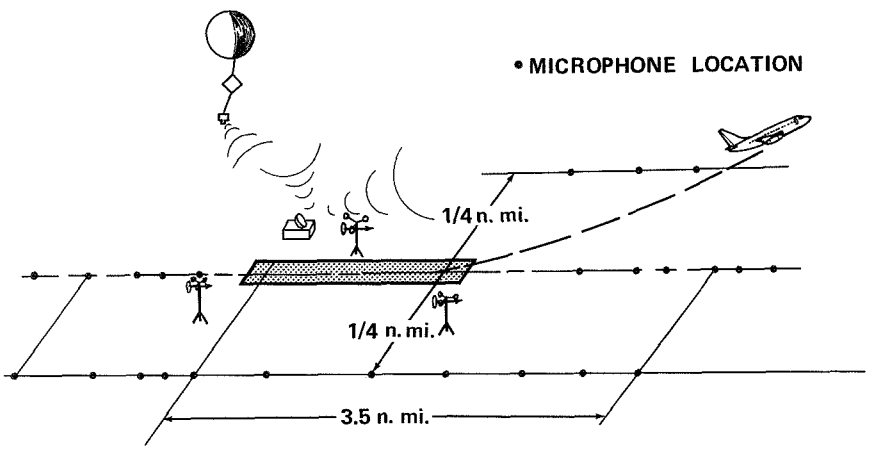

Figure 1.- Test site.

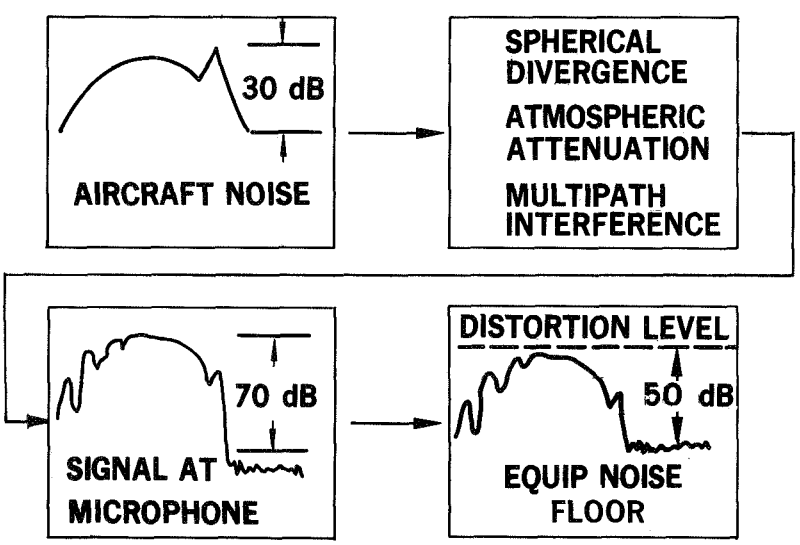

Figure 2.- Sources of error and distortion in aircraft noise measurements.

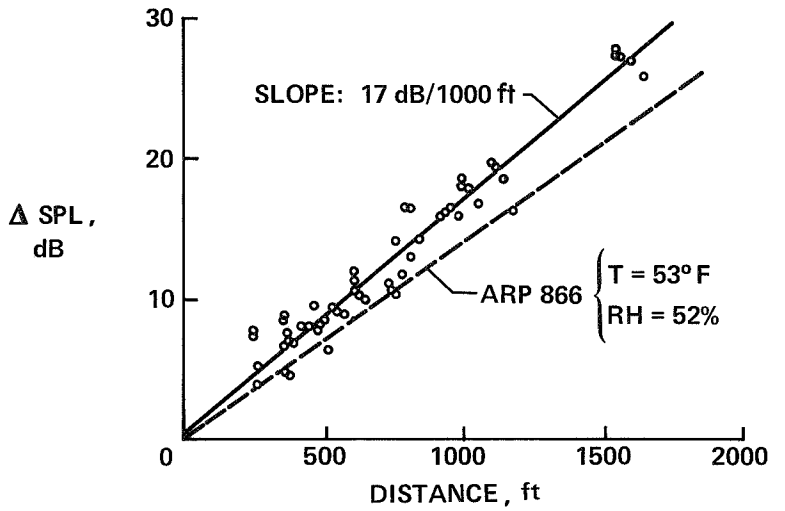

Figure 3.- Attenuation at a given frequency of 5000 hertz.

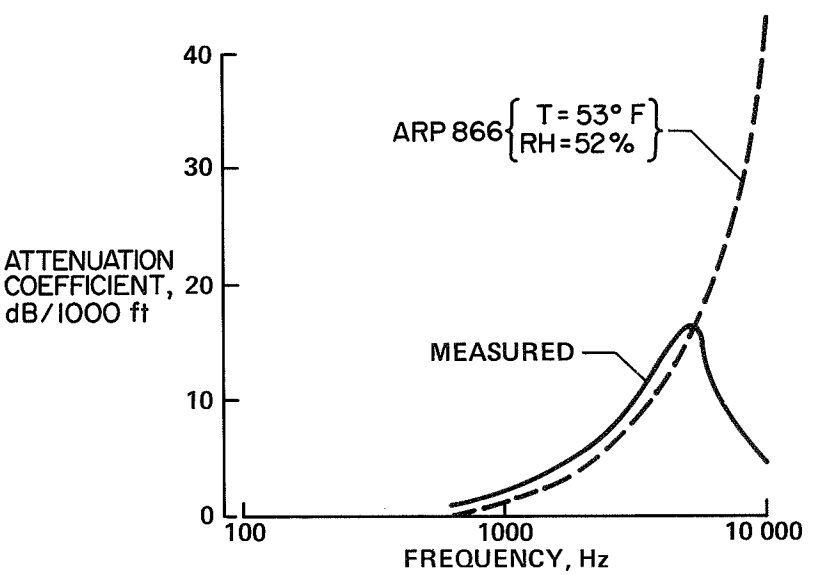

Figure 4.- Measured versus predicted attenuation for example 1.

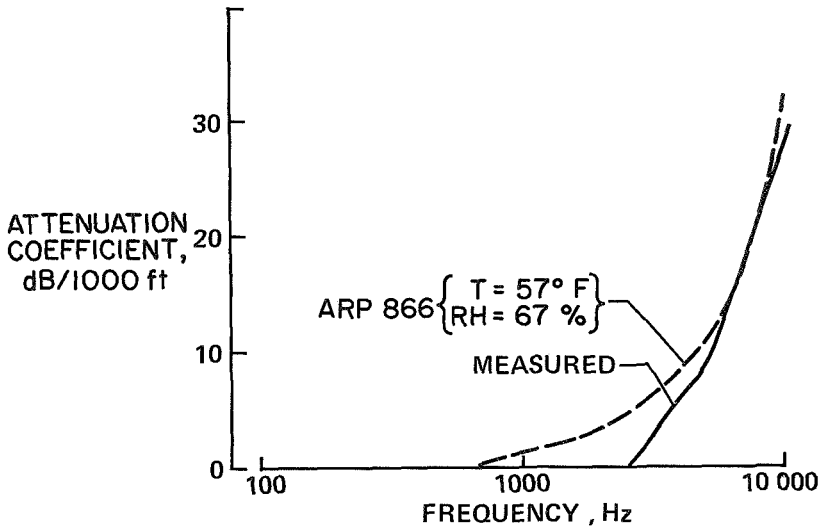

Figure 5.- Measured versus predicted attenuation for example 2.

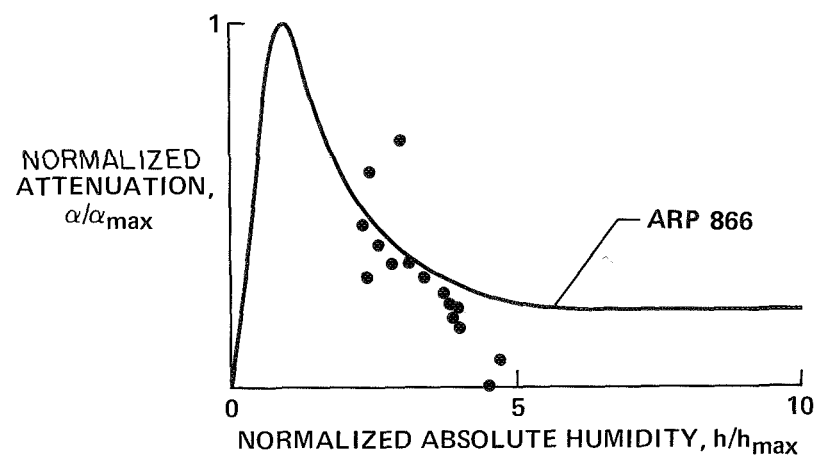

Figure 6.- Normalized attenuation.